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Adverse aeroelastic responses and related instabilities may affect the performance of many advanced air vehicle configurations. These responses are linked to nonlinearities within the aeroelastic system and have resulted in responses such as store-induced limit cycle oscillations (LCOs) and residual pitch oscillations (RPOs). As concepts for future aircraft designs are pursued, the source of these instabilities must be characterized. The primary objectives of this research are to investigate the presence of nonlinear pathologies such as LCOs and system resonances in aeroelastic systems; characterize the signature of such responses in the coupled nonlinear aerodynamic, structure, structural dynamic system; and, and examine passive suppression concepts. These research activities have been directed toward an explanation of nonlinear behavior found in aircraft systems. In particular, interes has been focused on store-induced limit cycle oscillations ("wing-with-store flutter") that exist, but not predicted with current approaches. We considered an aeroelastic system that was coupled by nonlinearities, possessed an external forcing, and satisfied conditions in which the frequencies were commensurate. Also, we examined LCO's induced by continuous hardening-type nonlinearities in structural stiffness.

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THEORETICAL AND EXPERIMENTAL INVESTIGATIONS OF INTERNAL RESONANCES, AND RELATED BEHAVIOR, IN NONLINEAR AEROELASTIC SYSTEMS

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Objectives

Adverse aeroelastic responses and related instabilities may affect the performance of many advanced air vehicle configurations. These responses are linked to nonlinearities within the aeroelastic system and have resulted in responses such as store-induced limit cycle oscillations (LCOs) and residual pitch oscillations (RPOs). As concepts for future aircraft designs are pursued, the source of these instabilities must be characterized. The primary objectives of this research are to investigate the presence of nonlinear pathologies such as LCOs and system resonances in aeroelastic systems; characterize the signature of such responses in the coupled nonlinear aerodynamic, structure, structural dynamic system; and, and examine passive suppression concepts. The research matures our analytical approach that examines nonlinear aeroelastic response and stability, and is complemented by benchmark experimental investigations designed to investigate nonlinear dynamic behavior of aeroelastic systems.

Status of Effort

These research activities have been directed toward an explanation of nonlinear behavior found in aircraft systems. In particular, interest has been focused on store-induced limit cycle oscillations ("wing-with-store flutter") that exist, but not predicted with current approaches. The investigations examined nonlinear responses for a system constrained to a two degree-of-freedom system and included benchmark validation experiments. The investigators have examined nonlinearities in the system due to aerodynamic stall (analytically and numerically) and have examined nonlinearities due to structural behavior (analytically, numerically, and experimentally). These responses suggested a possible triggering mechanism that leads to store-induced limit cycle oscillations may be the combination of nonlinear sources, and consequently new studies have considered all sources simultaneously. Most recently, a model has been formulated in which model-based simulations of a continuous wing include a simultaneous treatment of structural, store-induced, and aerodynamic nonlinear contributions. Attention is focused to the possible existence of auto-parametric (internal) resonances, subharmonic and superharmonic excitations, and related responses in the nonlinear aeroelastic environment. Benchmark tests of a new wing section with leading edge and trailing edge control surfaces are complete for the static configuration, and the model will lead to future benchmark efforts to consider higher degree-of-freedom systems. The wing section design included a store model such that kinematics may be tuned to induce nonlinear coupling via kinematics.

During the previous reporting cycles the investigator described studies of internal resonant–type behavior and associated instabilities in aeroelastic systems (see Gilliatt, Thompson). In these efforts, we considered an aeroelastic system that was coupled by nonlinearities, possessed an external forcing, and satisfied conditions in which the frequencies were commensurate. In these systems, the natural frequencies depended upon the presence of aerodynamics and flowfield conditions. System parameters were chosen such that the near-integer frequency ratios of 3:1, 2:1, and 1:1 were achieved as the

freestream velocity was increased. Gilliatt showed that for a system with a cubic nonlinearity, a large growth in amplitude and an exchange in modal energy occurred as the system passed through a 3:1 frequency ratio.

Also, we examined LCO's induced by continuous hardening-type nonlinearities in structural stiffness (see Thompson). Such nonlinearities have been substantiated by stiffness measurements of high performance aircraft. The system contained kinematic nonlinearities that are representative of store loadings, yet the nonlinear pitch stiffness was found to be dominant. The approach identified conditions exist under which resonance-type terms led to nonlinear responses. Simulation and analysis showed that when system damping was low, the system clearly exhibited nonlinear interaction between modes. It was shown that although certain forcing conditions applied to the damped system may appear negligible under certain circumstances, these same forcing conditions led to a relatively large amplitude LCO under other conditions. The system clearly showed an exchange of energy between modes when commensurate conditions were present. The damped system showed large amplitude LCOs when an external forcing was combined with a sufficiently large disturbance. Thus, such a forcing plus disturbance may result in the presence of relatively large amplitude LCOs when a (seemingly unimportant) forcing function is present.

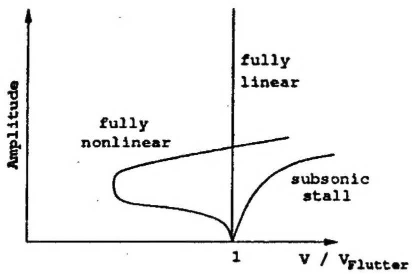
Our efforts were supported by validation benchmark experiments. We developed and reported a wind-tunnel model support test apparatus that permits prescribed experiments of nonlinear aeroelastic behavior. Studies of large amplitude LCO aeroelastic instabilities arising from spring-hardening (stiffness) nonlinearities were conducted. We completed construction of a new wing section that has both leading edge and trailing edge actuators for related research. This wing section also was designed to facilitate experiments with a store for the purpose of examining store-induced LCOs.

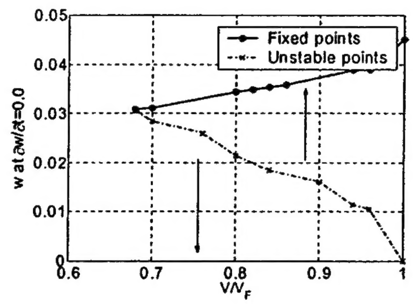
We submit that a thorough understanding of nonlinear aeroelastic response requires simultaneous and consistent treatment of all nonlinearities. More recently, investigations have focused on limit cycle oscillations of a cantilevered wing-with-store configuration (see Kim). Full system nonlinearities are retained, and include nonlinear aerodynamic effects (e.g., incompressible quasi-steady stall w/o hysteresis), coupled responses from the structure (e.g., large deformation, geometric stiffening), and store-related kinematics and dynamics.

Herein, unsteady aerodynamic loads are modeled with a quasi-steady approach with stall. However, the investigator has expanded these capabilities to include more robust aerodynamic theories (see Strganac). The structural dynamics for the cantilevered wing are modeled by the nonlinear equations of motion for a beam. The effects of general store-placement are modeled by the nonlinear equations of motion related to the position-induced nonlinear kinematics. Chordwise deformations of the wing surface, as well as pylon and store flexibility, are assumed negligible. We have found that in-plane bending responses may lead to some resonances, and in-plane responses may be necessary to completely predict LCOs.

Accomplishments / New Findings for FY 2003

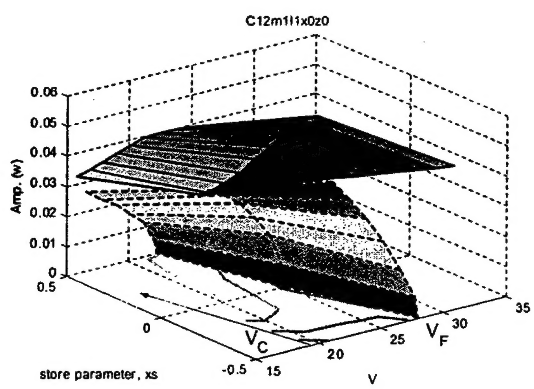
Nonlinear responses are studied by examining bifurcation and related phase portrait characteristics. Indirectly, a bifurcation diagram is constructed using the response characteristics at several velocity ratios for a specific configuration. Parametric investigations of sensitivity to store-to-wing mass, inertia ratios and store-position are conducted to examine parameter-dependent bifurcation characteristics. To illustrate these characteristics, we provide the following figures.





Bifurcation diagrams are derived from Poincaré maps of system response.
Left view: Possible Store-induced LCO cases are illustrated. Right view: LCO response appears from the upper (stable) branch of the subcritical bifurcation for a wingtip store cg position at 20% chord.

The figures represent the bifurcation characteristics of the system studied. The case in which all nonlinearities are included ("fully nonlinear" curve) represents the only sub-flutter LCO case that occurs. Linear (classical flutter) and supercritical LCO (for example, due to stall) behavior is shown. The right figure is indicative of the subcritical bifurcation case that occurs for several wing-with-store configurations. The character of this bifurcation, including features such as the existence of the LCO, lowest onset speed, location of the separatrix, and amplitude of the stable LCO, depends on system parameters such as store mass, store location, and pylon length. In the next figure, the effect of a change in parameter properties on the bifurcation surface is shown in a three-dimensional

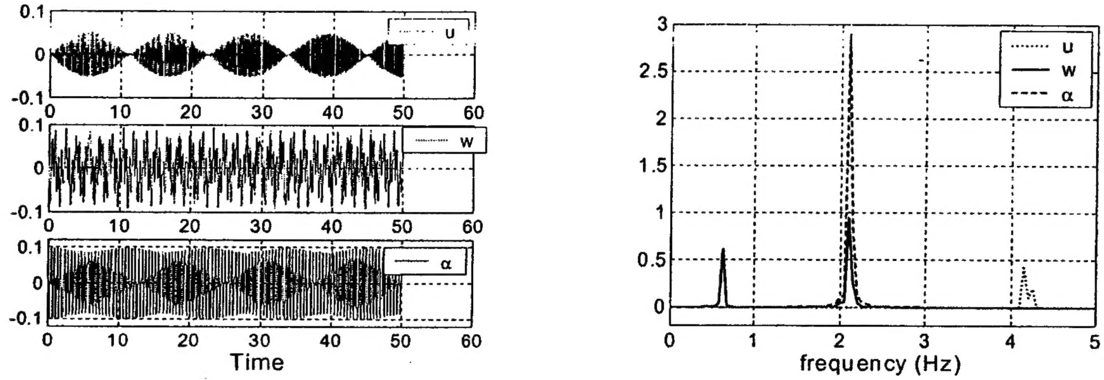


A 3-D Bifurcation surface shows parametric effects on the separatrix and stable LCO.

The effect of chordwise position of the wingtip store is shown in the figure. The subcritical bifurcation shifts to lower velocities as the cg is moved aft. The contours on

the lower plane represent the amplitudes of the LCO. V_C represents the critical velocity at which the bifurcation first occurs, V_F represents the flutter velocity found for the linearized system.

We continue to place particular attention in internal resonance. The addition of the in-plane response has identified nonlinear couplings that lead to a modulation of energy between in-plane motion and pitch responses. As shown in the figure below, for a system tuned to a 2:1 quadratic internal resonance (herein, controlled by span and velocity), a resonance type behavior occurs when $\omega_{in\text{-}plane} = 2\ \omega_{pitch}$. Interestingly, and confirmed by analysis, these quadratic-type resonances are triggered by in-plane motion.



Internal resonance occurs when $\omega_{in\text{-}plane} = 2\ \omega_{pitch}$

Summary Comments

LCO is predicted and, of specific interest as observed in flight tests, such response is found at flowfield conditions below those at which flutter is predicted by linear analysis (see Denegri's "Typical LCO" responses). As also observed in flight tests, results indicate a dependence upon initial conditions related to flowfield disturbances and/or flight maneuvers as well as flight conditions. Under certain flight conditions, an unstable limit cycle is found which partitions the response, depending upon the magnitude of initial condition, to either a stable limit cycle oscillation or a subsidence to zero. Such results provide an explanation for the hysteresis that occurs in the flight conditions between the onset and disappearance of limit cycle oscillations.

Store-induced LCO originates from a subcritical Hopf bifurcation in which the magnitude and existence of the LCO depends upon velocity and initial condition (i.e., it depends upon the magnitude of pilot control input, gust load, turbulence level, or maneuver loads). Such sub-flutter, initial-condition dependent response mimics the characteristics of LCO incidents found during flight tests.

Herein, the only case that exhibits LCO below the linear flutter velocity possesses several sources of nonlinearity. Model development for tools to predict nonlinear aeroelastic response should include simultaneous treatment of all sources of nonlinearities. Furthermore, results indicate a sensitivity to in-plane stiffness leading to other nonlinear couplings.

Flight tests and ground tests have shown evidence, albeit limited, that autoparametric (internal) resonances exist. Analysis is promising yet the proper treatment of higher-order nonlinearities remains elusive. Some flight tests have shown responses traced to in-plane fuselage dynamics. These results suggest other modal behavior must be considered. Hall describes saturation phenomena related to internal resonance behavior. Interestingly, Denegri discusses "Atypical LCOs" in which amplitude is sustained regardless of flight condition. These responses are too similar to be ignored.

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